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A rapid sample-exchange mechanism for cryogen-free dilution refrigerators compatible with multiple high-frequency signal connections

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ABSTRACT

Researchers attempting to study quantum effects in the solid-state have a need to characterise samples at very low-temperatures, and frequently in high magnetic fields. Often coupled with this extreme environment is the requirement for high-frequency signalling to the sample for electrical control or measurements. Cryogen-free dilution refrigerators allow the necessary wiring to be installed to the sample more easily than their wet counterparts, but the limited cooling power of the closed cycle coolers used in these systems means that the experimental turn-around time can be longer. Here we shall describe a sample loading arrangement that can be coupled with a cryogen-free refrigerator and that allows samples to be loaded from room temperature in a matter of minutes. The loaded sample is then cooled to temperatures ~10 mK in ~7 h. This apparatus is compatible with systems incorporating superconducting magnets and allows multiple high-frequency lines to be connected to the cold sample.

1. Introduction

Over the past century studying condensed matter systems at extremely low temperatures, and often in extremely high magnetic fields, has lead to the discovery of several new states of matter, such as: superconductivity in mercury [1]; superfluidity in ^{4}He [2,3]; superfluidity in ^{3}He [4]; the integer quantum Hall effect in silicon MOSFET devices [5]; the fractional quantum Hall effect in GaAs–AlGaAs heterojunctions [6].

More recently there has been a drive to harness these quantum systems to realise devices that exploit their quantum nature, for example in the field of quantum information processing [7], with the realisation of a general quantum computer [8] being the holy grail. Inevitably the development of these quantum devices requires temperatures <10 mK, and possibly magnetic fields >10 T, however in addition to these environmental constraints device characterisation and development also requires the necessary experimental services be installed at the sample position: most challengingly high-bandwidth, high-fidelity micro-wave cabling.

In the following sections we describe briefly a suitable experimental environment for quantum device development (or any other experiments requiring high-frequency measurements at low-temperatures), then we show that device characterisation is more convenient with a sample loading mechanism, and describe its realisation, operation and performance, before providing a brief conclusion.

2. Experimental environment

Pulse-tube precooled dilution refrigerators [9] are becoming increasingly popular. Initially this popularity stemmed from the fact that they were cryogen-free, meaning that they could be installed at institutions without the associated low-temperature research infrastructure, such as a helium liquefaction plant, or in remote locations. Additionally, there are benefits from an operational point of view as such systems can be automated to a higher degree than their "wet" counterparts. It has also been found that these cryogen-free systems have further benefits when compared to wet systems with regards to the installation of experimental services, as will be discussed in the following sections, and this has driven the recent rise in their uptake.

With the installation of high-frequency wiring these refrigerators have been developed into measurement systems for circuit quantum electrodynamics [10] and superconducting qubits [11]. The integration of superconducting magnets [12], with the entire system able to be run from a single pulse-tube cooler, has enabled

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a wider range of experiments (those requiring magnetic fields) to be performed using this cryogen-free technology [13].

2.1. Low-temperatures and high magnetic fields

Cryogenic systems using liquid helium are usually designed to minimise its consumption. This is because liquid helium is expensive, refilling the system can be time consuming, and refilling the system may perturb the experiment to an unacceptable level. The central neck of a cryostat is often responsible for the biggest single heat load into the helium bath, and as a result these necks are usually made as long and as narrow as possible. Dilution refrigerators designed to be inserted into such a cryostat have to inherit this aspect ratio, which has tended to limit the experimental real estate available for the installation of services.

With no boil-off considerations, cryogen-free systems have evolved to be much wider than their wet counterparts with experimental plates (to which services can be mounted) typically several hundred mm in diameter [12]. This has enabled more and/or more complex services to be installed on dilution refrigerator systems, in particular bulky signal conditioning elements such as cryogenic amplifiers, microwave components (bias-tees, circulators, switches, etc.) and filtering (such as metal powder filters, for example [14] and the references therein).

Cryogen-free systems can also be designed without the need for a low-temperature, vacuum-tight vessel, the so called inner vacuum chamber (IVC), which makes the routing and heat-sinking of the installed services much more straightforward, see Section 2.2.2.

The range of magnets that are able to be produced for cryogen-free operation is also continually expanding with higher fields (>16 T) and vector-rotation (>6–1–1 T) available.

For these reasons cryogen-free dilution refrigerators with integrated magnets have become the workhorse of quantum device development laboratories around the world.

2.2. High-frequency wiring

As was noted in Section 1 high-fidelity, high-bandwidth wiring is an experimental requirement for quantum device development applications. In addition to the quality of the signal transmission performance of these cables, they also need to be thermally anchored adequately to ensure that they do not affect adversely the base temperature performance of the system onto which they are installed. In this section we shall: review various options for the coaxial lines and some of the materials available for the lines themselves, and discuss their relative merits; describe a convenient method for mounting multiple high-frequency lines onto a dilution refrigerator; quantify the frequency dependence of signal transmission of installed lines with S_{12} measurements made with a vector network analyser; comment on the heat load to the mixing chamber likely to result from the installation of the type of wiring described.

2.2.1. Coaxial cables and materials

To date, most high-frequency cabling installed in dilution refrigerators have been of "semi-rigid" construction with the UT-85 cable (having an outer diameter of 85/1000 of an inch, approximately 2.16 mm) being commonly used. The optimal choice of coaxial cable, in terms of both size and material, depends on its intended application. Typically coaxial cables are used to (1) improve noise immunity for "small" signals and/or (2) transmit high-frequency signals to/from the sample.

If using coaxial cables for either of these reasons one should ensure that the cables themselves are suitable for the intended application. For dilution refrigerator based experiments, this suitability is generally determined by two key parameters: the heat load to the experiment due to the thermal conductivity of the cable; and its (frequency dependent) attenuation. Both of these parameters are affected by the choice of the cable geometry (size) and conductor materials.

The heat load conducted to the coldest parts of the dilution refrigerator is always to be minimised. For a given choice of coaxial cable material and geometry there is a lower limit to this heat load determined by the bulk thermal conductivity of the cable materials. This limit is approached as the cable (both the inner and outer conductor) is perfectly thermally connected to every available temperature stage in the refrigerator, of course the conducted heat load can be much higher than this limit if the thermal connections are inadequate. A convenient method of installing semi-rigid coaxial cables into a dilution refrigerator that gives good thermal performance is discussed in Section 2.2.4. The heat load can only be reduced further by using either cables with a smaller cross sectional area and/or cables made from materials with a lower thermal conductivity, however such changes may well have implications for the cable attenuation.

The frequency dependent attenuation of a coaxial cable is determined by the cable geometry (outer diameter of the inner conductor and inner diameter out of the outer conductor), the (temperature and frequency dependent) resistivity of the conductor materials and the dielectric losses [15]. In general smaller diameter cables have higher attenuation at high frequencies than larger diameter ones, and cables manufactured from materials with higher bulk resistivity have higher attenuation (at a given frequency) than low resistance ones. Depending on the application, this increase in attenuation can be fortuitous or problematic. In applications where coaxial cables are used for noise immunity for small, low-frequency signals, having increased attenuation at high frequencies is advantageous: in fact "lossy" coax cables have been used as microwave filters [16].

However, for high-bandwidth signals the change in attenuation, α, with frequency, f, is undesirable as it results in the "shape" of signals (in the time-domain) being modified as they propagate along the cable and this can cause problems with, for example, high-fidelity qubit control. Techniques borrowed from the NMR/MRI world for pulse preshaping using *a posteriori* knowledge of the cabling transfer function [17] can be applied to compensate for this effect, but it would still be advantageous to keep the frequency response of the cable as flat as possible. Using (lots of) large-diameter low-resistance cables can be incompatible with experiments at dilution refrigerator temperatures, as the thermal and electrical conductivity of a normal metal are closely related [18]. However, superconducting cables made from Nb, or preferably NbTi (due to its higher critical field and temperature, and lower thermal conductivity), can be used. Below their superconducting transition temperature these cables provide very low attenuation and have a small thermal conductivity [15] so in many cases are the ideal solution to this problem. However, with cryogen free dilution refrigerators enabling experiments over extended temperature ranges [12] some care needs to be taken, as the electrical performance of these lines will change (attenuation will increase) dramatically above their transition temperature.

One final point is that the desire to keep $\frac{d\alpha}{df} \approx 0$ is *not* the same as keeping $\alpha \approx 0$. Indeed, the types of cables described here are very good at transmitting "thermal noise" from warmer parts of the refrigerator to colder ones, equating $h\nu \approx K_B T$ gives a photon frequency of 20 GHz at 1 K and UT-85 cables operational range can extend to >60 GHz [19], and so having some attenuation in the line is desirable to reduce these thermal perturbations. Attenuators with a flat frequency response, compatible with cryogenic temperatures [20], can be used to increase the attenuation of a line whilst avoiding the complications of distorting high-bandwidth signals. Details of measurements of such lines will be given in Section 2.2.3.

2.2.2. High-frequency wiring cartridges

As described in Section 2.2.1, for some experiments small diameter coaxial cables with high attenuation at high-frequencies can be appropriate. For example, UT-13 cables have an outer diameter of approximately 330 μm and can be installed and thermally anchored like flexible "DC" wiring. In this section we focus on semi-rigid cables and describe a convenient method of installing multiple, configurable, semi-rigid coaxial lines into a dilution refrigerator in a way that gives good electrical and thermal performance and allows for the cable assemblies to be rapidly demounted and modified if necessary.

Cryogen-free dilution refrigerators typically have several large (40–100 mm diameter) line-of-sight (LoS) ports that allow connections between the room temperature top-plate and the mixing chamber plate. Whilst traditional wet dilution refrigerators also often feature LoS ports they tend to be less numerous and of smaller diameter. Wet systems also require an IVC and so services need to be installed in vacuum tubes from room temperature to 4 K, making the thermal anchoring of the installed services more difficult (services can of course be thermalised by bringing them through the main helium bath, but then cryogenically compatible, hermetically sealed feed-throughs are required to bring the services into the IVC).

A typical cryogen-free refrigerator will have experimental plates that can be used to thermally anchor wiring at temperatures of approximately 50 K, 3 K, 0.8 K, 100 mK and the mixing chamber at around 10 mK. The wiring cartridge shown in Fig. 1 has anchoring plates at each temperature stage. It has been found that the use of bulkhead connectors at each of these plates is an effective way to thermalise both the inner and outer conductors of the cables [21], and provides a convenient mounting point for any attenuators that may be added to the lines at any of the stages. The cartridge is designed to be able to be loaded into the system either completely assembled from the top, or without the top plate fittings from below. Once the cartridge is installed, split clamp plates are used to make thermal contact between the cartridge and the refrigerator. The fact that the entire wiring assembly can be removed in one piece allows for bench testing of the microwave lines prior to installing them into the system. It also means, for example, that should there be a desire to change installed attenuators for ones with a different attenuation value the assembly can be removed from the refrigerator by simply opening one room temperature o-ring seal and loosening the clamping bolts. With the assembly removed, the microwave lines or attenuators, between the bulkhead connectors, can be reconfigured and tested before being refitted to the system.

2.2.3. Transmission measurements

The microwave performance of installed coaxial cable assemblies has been measured with an Antitsu model MS2028C/2 vector network analyser [22] which recorded the scattering parameters at frequencies up to 12 GHz. Typical curves between 5 kHz and 8 GHz are shown in Fig. 2. The S_{12} parameter can be associated with the total attenuation in the line and the measured values agree well with cable manufactures' data for expected values of the frequency dependent attenuation (per unit length) of the cables they produce [19,23], in this case the coaxial cable sections themselves were silver-plated stainless steel inner conductor, stainless steel outer conductor from room temperature to the 4 K plate, and NbTi inner and outer from 4 K to the mixing chamber. Faults with the coaxial cables, such as loose connectors or cracked solder joints, can be identified from scattering parameter measurements [24], and for the cables installed on these systems typically result in additional attenuation (reflection) features at frequencies of a few GHz, Fig. 2.

2.2.4. Thermal performance

As discussed in Section 2.2.1 there is a lower limit to how far the heat load from installed cabling can be reduced. Here we examine the residual heat load onto the mixing chamber of a cryogen-free dilution refrigerator when wiring cartridges are installed. This heat load can be extracted using knowledge of the cooling power of the dilution refrigerator at the temperatures of interest. With knowledge of the cooling power, the base temperature of a refrigerator with and without wiring installed can be compared and the heat

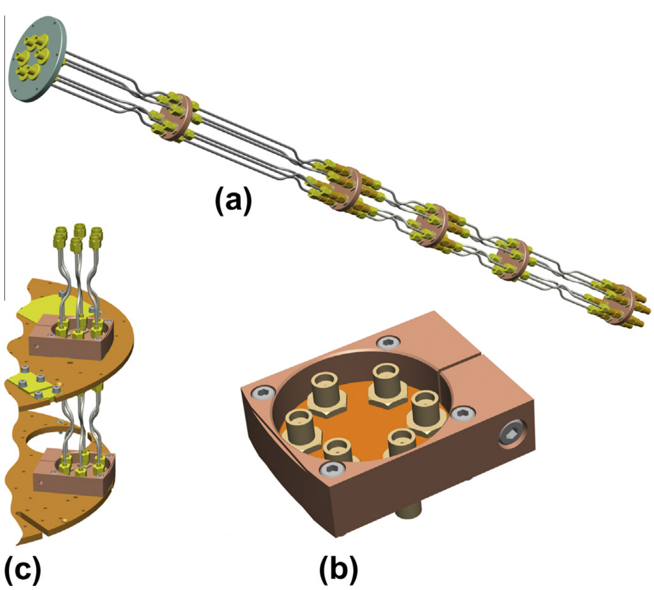


Fig. 1. A wiring cartridge for a cryogen-free dilution refrigerator: (a) Shows a fully assembled cartridge with hermetic feed-throughs on the room temperature top plate and additional attenuators installed above and below some of the thermal stages. (b) Shows the detail of a split clamp used to thermally anchor the cartridge to the refrigerator and the bulkhead connectors through the cartridge plate. (c) Shows how such a section of such a cartridge could be installed through a line-of-sight port of a dilution refrigerator.

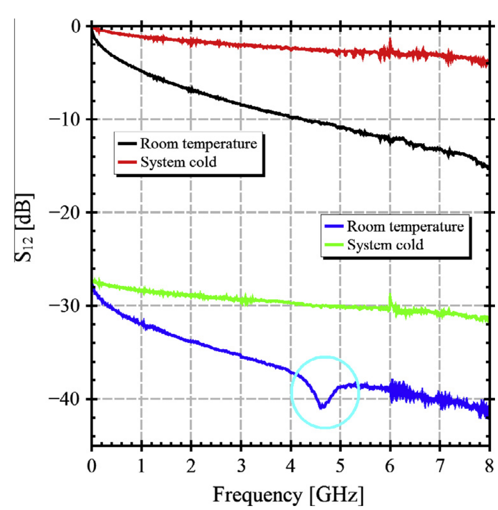


Fig. 2. Scattering parameter measurements on coaxial cables installed in wiring cartridges. The red and black traces show lines with no additional attenuation installed. The green and blue traces show lines with an additional 28 dB of in-line attenuation. The reduction in the attenuation between room temperature and the system being cooled is due principally to sections of superconducting coaxial cable cooling below their transition temperature. The dip in the attenuation on the blue trace (circled) was due to a loose connector in the cartridge assembly, this was corrected prior to the cartridge being installed into the system and cooled. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

leak extracted from the difference in these temperatures. For these measurements three wiring cartridges, each containing eight UT-85 coaxial lines (24 lines in total) manufactured from cupronickel conductors, were installed onto a Triton200 [25] dilution refrigerator system, as show in Fig. 3. After the addition of the wiring cartridges the temperature of the plate mounted at the end of the continuous heat exchanger, colloquially know as the "100 mK plate", had increased from 65 mK to 120 mK as measured with a resistive temperature sensor [26]. The base temperature of the dilution refrigerator, measured using a nuclear orientation thermometer [27], was found to have risen to 9.1 mK, corresponding to an increased heat load of ≈600 nW. Extrapolating available data for the thermal conductivity of cupronickel [28] to 100 mK and calculating the anticipated heat load conducted through 24 UT-85 coaxial lines with the geometry defined by manufactures [23] accounts for ≈200 nW of this increase, with a further additional ≈300 nW expected through the stainless steel refrigerator support structure, calculated using published values for the thermal conductivity [29], due to the increase in temperature of the 100 mK plate.

3. Rapid sample exchange

In Section 2 it was shown that cryogen-free dilution refrigerators integrated with superconducting magnets provide an ideal environment for quantum device development experiments due to their ease of use and the convenience of installing experimental services. These systems do, however, have one significant drawback compared to their wet counterparts as the integrated superconducting magnets become larger: the experimental turnaround time. High-field cryogen-free magnets can have masses well in excess of 50 kg and require enthalpy changes of several MJ to cool from room temperature to 4 K. The pulse tube coolers used in these systems typically have cooling powers at the second stage of ≈140 W at room temperature, falling to ≈1 W at 4 K [30]. This limited cooling power means that the initial cool down from room temperature can take much longer than wet systems (which can be cooled quite quickly if the cryogen boil-off can be tolerated).

This drawback can be overcome with a method of exchanging samples that keeps the rest of the system (and the magnet in particular) cold. To be useful for a wide range of experiments, such a mechanism must provide multiple high-frequency lines to the sample and provide sample temperatures comparable to the base temperature of the refrigerator. In the following sections we describe the design, construction and performance of such a sample exchange mechanism.

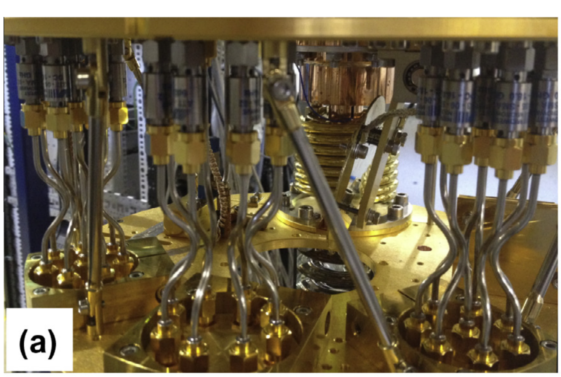
3.1. The sample exchange concept

Attaching a sample and experimental wiring directly to a probe and loading the entire assembly into a dilution refrigerator has been attempted, but it was found that the resulting thermal performance and limited space is incompatible with multiple high-frequency lines and additional microwave components (amplifies, filters, etc.), see Section II A of [31].

An alternative approach to sample loading, as also implemented in [31], is to leave the experimental wiring on the refrigerator, where it can be efficiently thermally anchored, in this case by using the wiring cartridge design discussed in Section 2.2, and to load a "sample holder" to connect to this installed wiring. Additionally, this means that the full sample space of the refrigerator can be utilised to install other components into the experimental wiring circuits which may not fit onto a smaller diameter probe. Loading only a sample holder into the refrigerator introduces the complication of requiring demountable microwave connectors, but in the following sections we show that this requirement can be fulfilled. It is often also desirable to be able to bias or ground electrical connections to delicate samples during the cool down process to prevent, for example, electrostatic sample damage. This is accomplished with a "make-before-break" arrangement whereby all DC and microwave connections to the sample holder are individually connected to room temperature connectors on the loading probe. As will discussed in Section 3.1.2 the sample holder can also be made demountable, allowing the loading probe to be removed after the sample is attached to the refrigerator.

With a cryogen-free system without an IVC there is no preferred direction for sample loading. Samples can either be introduced from the top of the system using a top-loading load-lock (TLLL) or from below using a bottom-loading load-lock (BLLL). TLLLs require a (central) LoS access port through which the sample can be introduced, and BLLLs require access through the vacuum and radiation shields through which the sample can pass. The distance from the refrigerator top-plate to the magnetic field centre-line is normally longer than that from the bottom of the system to field centre, so systems with TLLLs tend to require more ceiling height for operation than systems with BLLLs. However, the sample holder and loading arrangement for BLLL systems needs to be able to pass into the bore of the system magnet whereas in TLLL systems the thermal and electrical connections can be made above the magnet, offering more space for these connections.

Both the TLLL and BLLL require move-able baffles to allow the sample holder to be introduced into the system without leaving an unacceptable heat load from 300 K blackbody radiation in



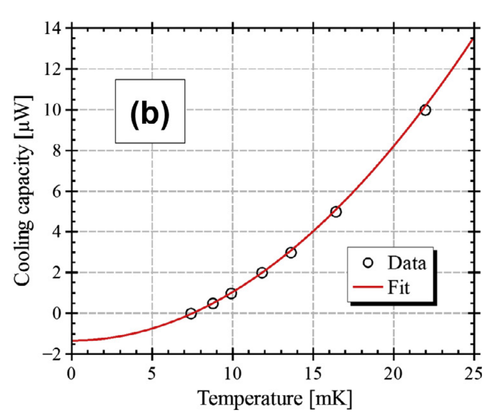


Fig. 3. (a) An image showing how multiple coaxial cable cartridges can be installed onto a dilution refrigerator system. In-line attenuators are visible below the upper plate, which is at the position of the dilution refrigerator still. (b) A plot of the typical cooling capacity available at the mixing chamber of such a dilution refrigerator. The fit in the plot is of the form $y = ax^2 - b$.

normal operation. For TLLL systems these can be controlled with a drive rod mechanically connected to the room temperature top plate. For BLLL systems it is more convenient to make these baffles spring-loaded as the baffles themselves are attached to demountable radiation shields.

3.1.1. Connectors

The choice of connectors is critical to the microwave performance of a cable assembly. With standard UT-85 type cables the usual room temperate choices are SMA [32] connectors for operation up to 18 GHz and SK [33] connectors for operation up to 40 GHz. Both of these connectors are screw lock, so unsuitable for push fit applications, the BMA [34] connector range is a blind-mate equivalent of the SMA connector, but suffers from being rated only to ~20 GHz and being rather bulky (~10 mm diameter) which limits the density of connections.

SMP [35] connectors have the advantage of being blind-mate, small diameter (~3 mm) and rated for 40 GHz operation and so were selected to trial cryogenically. A test piece was made, Fig. 4 (upper panel), and mounted onto a cryogen-free 4 K platform as a test bed. This test bed was equipped with microwave cabling enabling round-trip attenuation measurements through pairs of the test connectors to be made from room temperature.

First the test piece was repeatedly mated and unmated to test the reliability of the connectors with S_{12} measurements made after every cycle, Fig. 4(b). The connectors were robust to this cycling, so the system was cooled and the round-trip attenuation monitored as a function of temperature, Fig. 4(c). There was no degradation in performance of the connectors with temperature, the overall reduction in the round-trip attenuation with temperature is due to the temperature dependence of the coaxial cable material (stainless steel) used between room temperature and the 4 K stage.

Connectors for multiple DC lines were also trialled cryogenically and a nano d-type connector [36] was chosen, principally due to its extremely small footprint.

3.1.2. The loading probe

The loading probe is essentially identical regardless of whether the system is top or bottom loading save for the direction of insertion. The loading probe consists of a vacuum lock which is mounted onto a gate valve on the top/bottom of the main vacuum chamber and evacuated prior to introducing the sample holder into the system. Optionally, the loading probe vacuum lock itself can be fitted with an additional gate valve to allow samples to be stored under vacuum prior to loading into the system, and after removal.

The sample holder is mechanically connected to drive rods which enter the vacuum lock *via* piston seals, and electrically connected to the biasing/grounding wiring on the probe. The drive rods can be used to position the sample holder at the docking station (detailed in Section 3.1.3). The sample holder is pushed into the docking station (making the electrical connections to the wiring installed on the refrigerator) and then bolted into place using the drive rods, utilising fasteners captive to the sample holder, to make the thermal connection. Typically 2, 3 or 4 (depending on the sample holder configuration) M4 threads are tightened to a torque of 5 Nm. A double thread arrangement allows the drive rods to then be disengaged from the sample holder and withdrawn from the system (breaking the electrical connections to the sample on the probe). Withdrawing the loading probe after the sample holder is loaded removes the requirement to thermally anchor the loading mechanism, and removes the associated conducted heat leak; thus the loaded sample holder has no impact on the base temperature performance of the refrigerator.

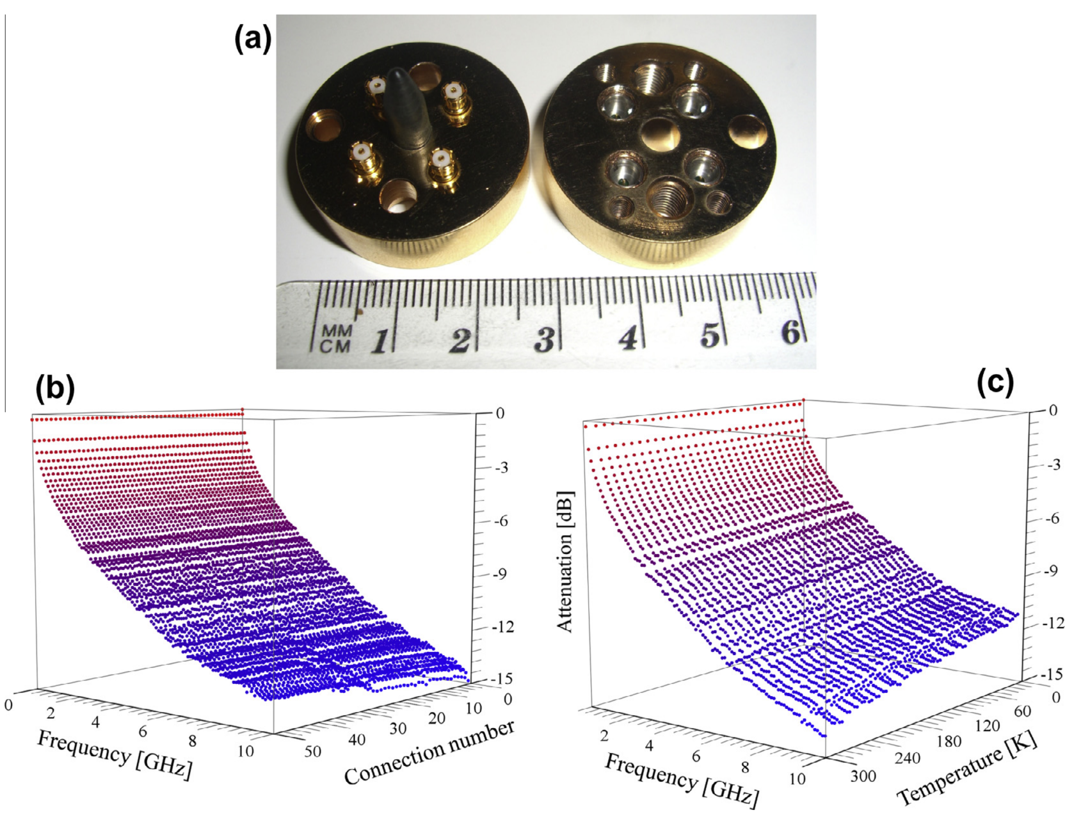


Fig. 4. (a) A test piece for SMP connectors. (b) The round-trip attenuation through pairs of the connectors measured at room temperature as a function of the connector mating cycle number. The data for the first 25 cycles are for one pair of connectors, the last 25 cycles are for the second pair. (c) The round-trip attenuation through the first pair of connectors measured at room temperature as a function of the temperature of the connectors.

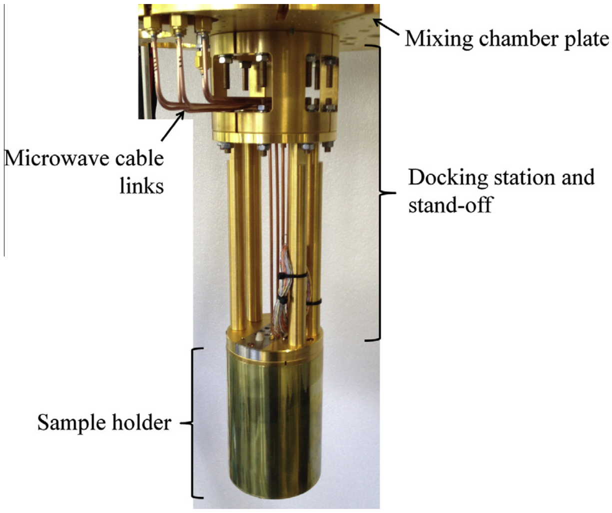


Fig. 5. A bottom loading sample holder, with its integrated radiation shield, connected to the mixing chamber docking station. The microwave cable links between the wiring cartridges and the docking station are visible.

3.1.3. The docking station

The docking station provides the mating electrical and thermal connections for the sample holder. The cabling attached to the refrigerator is routed to the docking station. For TLLL systems the docking station is a ring around the (central) LoS port, for BLLL systems it is a stand-off that brings the connection flange into the bore of the magnet. Typically 48 DC lines and 14 microwave cables can be connected to the docking station, however we note that it is straightforward to scale up the number of connectors, if required, particularly on TLLL systems as this can be achieved without the need for a larger magnet bore.

A BLLL sample holder attached to its docking station is shown in Fig. 5. Microwave cable links are fitted between the wiring cartridges, running through the refrigerator, and the docking station.

3.1.4. The sample holder

Examples of BLLL sample holders are shown in Fig. 6. In the figure, panel (b) is a design for integration with high-field magnets with 57 mm cold bore diameter, giving a clear diameter sample space inside the sample holder of $\sim$25 mm (reduced from the diameter of the sample holder by the drive rods internal to the holder required to make the bolted connections to the docking station, visible in the figure) by 90 mm long, symmetric about the field centre line of the magnet. Also shown (c) is a larger diameter sample holder for magnets with a 90 mm cold bore giving a clear sample space diameter of $\sim$50 mm.

Fig. 6(a) shows the mating surface of the BLLL sample holder. In particular the SMP connector "bullet" adaptors can be seen (the bullet has been removed from the lower left shroud). On the sample holder, "full detent" shrouds are used to retain the bullet. On the docking station smooth bore so called "catcher's mit" shrouds are used which allow for a certain amount of radial and axial misalignment between the shrouds during loading.

The sample holder features an integrated radiation shield, which also protects the sample mechanically during the loading and unloading process.

3.2. Sample cool-down

The procedure for loading a sample is straightforward. While the vacuum load-lock is evacuated the bulk of the mixture is removed from the refrigerator, for the refrigerators used in this work that are equipped with pre-cool lines [12] this takes around 15 min, and any superconducting magnet, if fitted, is de-energised. The sample is then introduced and connected to the mixing chamber, and the loading probe withdrawn. The refrigerator then re-cools back to its base temperature. The re-cooling and running to base can be automated, allowing a sample to be loaded in the evening and be at base temperature ready for measurements the following morning.

A typical cool down of a bottom loaded sample holder is shown in the left panel of Fig. 7. In this example the sample holder was

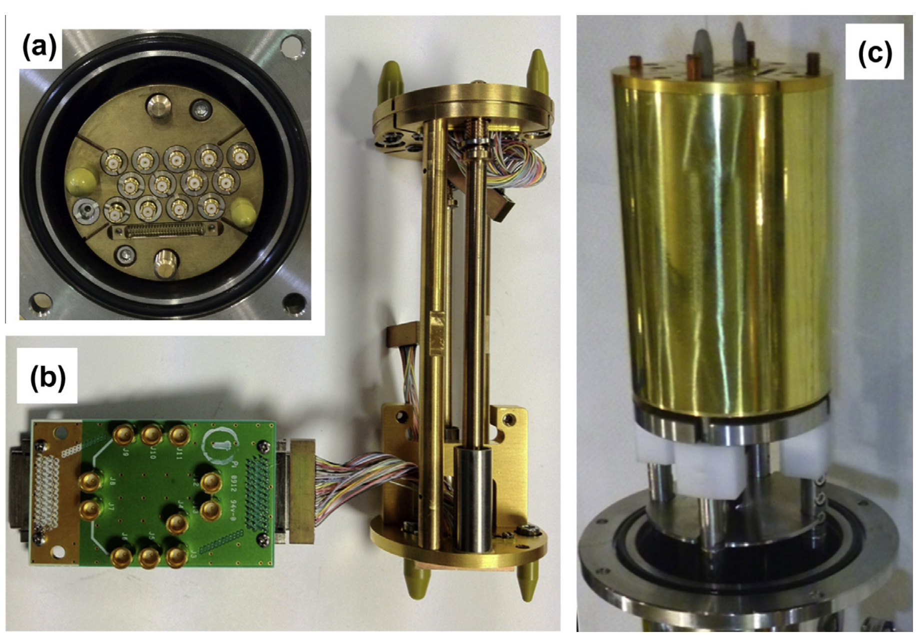


Fig. 6. (a) The mating surface of a bottom loading sample holder showing the 14 SMP connectors and 51-way nano d-connector. Two alignment pins are visible at the left and right of the holder and two M4 captive fasteners are visible at the top and bottom. (b) A bottom loading sample holder with the radiation shield removed. The wiring for grounding or biasing the sample whilst loading can be seen entering the sample holder from the bottom, and the experimental wiring entering from the top. Also shown is a PCB sample holder that could be used for mounting a sample into the holder. (c) A larger diameter bottom loading sample holder connected to the loading probe before being drawn into the vacuum load-lock. The four drive rods are visible at the base of the sample holder.

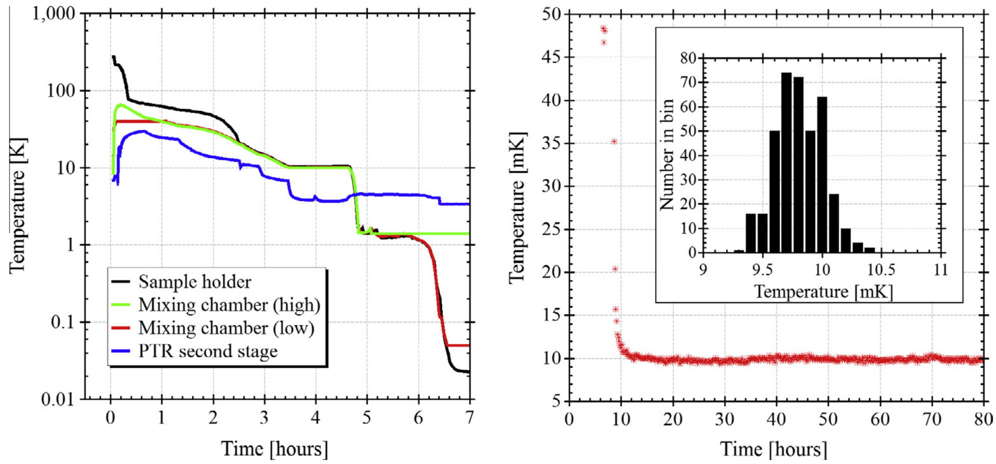


Fig. 7. The cool down of a bottom loading sample holder after being loaded onto a dilution refrigerator system. (left panel) The cool down from room temperature to mK temperatures in around 7 h. The high- and low-range mixing temperature sensors are calibrated between 325 K and 1.4 K, and 40 K and 50 mK respectively. At the lowest temperatures the measurements with resistive sensors are replaced with a nuclear orientation thermometer. (right panel) Cool down and base temperature measurements and (inset) the temperature stability at the sample position as measured with the nuclear orientation thermometer.

loaded onto a refrigerator equipped with eight of the silver-plated stainless steel upper, NbTi lower coaxial lines described in Section 2.2.3 and a further eight stainless steel lines. The base temperature attained at the sample position is shown in the right panel of Fig. 7, as measured with a nuclear orientation thermometer over a period of several days. The mean temperature at the sample position was found to be 9.85 mK.

3.2.1. Sample turnaround times

Whilst the cool down time of a loaded sample can be seen to be around 7 h from Fig. 7, the total turnaround time from removing one sample to having another cold is also of interest. As the loading probes and sample holders are interchangeable the optimum turnaround can be accomplished by having a second sample holder set up on a second loading probe whilst the cold sample is being removed. The removal of the mixture from the refrigerator and the unloading of the cold sample can be completed in around 20 min. If the loading probe is equipped with the additional gate valve discussed in Section 3.1.2, or if the sample can be vented to atmosphere whilst cold, then the two loading probes can be exchanged immediately, the vacuum seals can be demounted and remade in around 10 min. Finally the small volume of the load-lock can be evacuated and leak tested in around 20 min. The loading of the new sample and disconnection of the loading probe then takes a further 5 min.

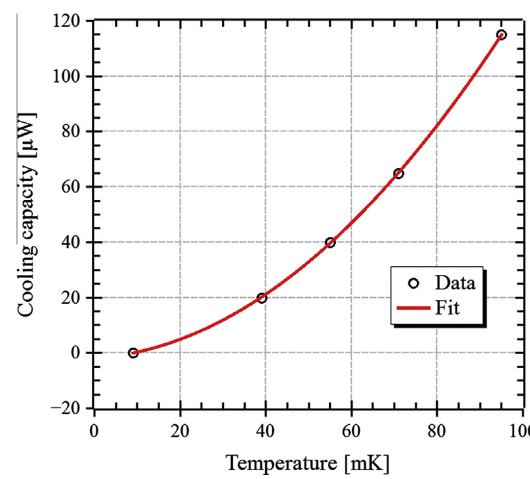


Fig. 8. The cooling power measured at the sample position on a top-loaded sample holder. The fit, a second-order polynomial, is included as a guide.

3.3. Cooling power at the sample stage

As all the experimental services are installed onto the refrigerator, and thermally anchored there, the cooling power

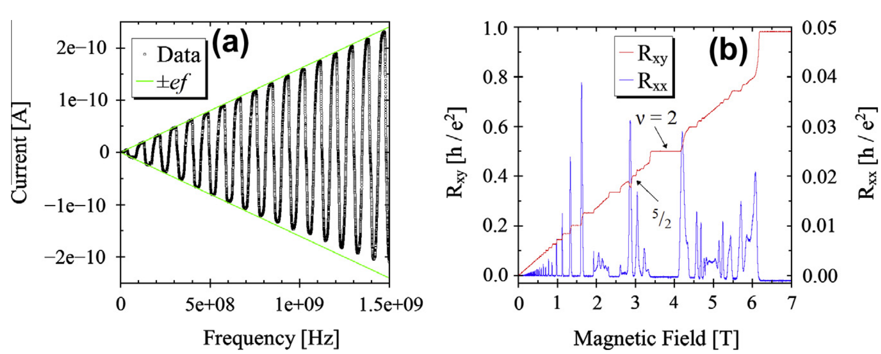


Fig. 9. (a) Gigahertz quantised charge pumping in a graphene double quantum dot device. Single electron pumps operating a high frequencies could allow for a new definition of the ampere. The straight lines represent $I = \pm ef$. The measured current oscillates between the quantised values because of a phase difference between the two drive signals resulting from unequal lengths of coaxial line. (b) The fractional quantum Hall effect measured in two-dimensional electron system. Quantised features at fractional values of $\nu > 2$ exemplify the low electron-temperatures attained in these measurements, from which a value of 15–20 mK can be inferred.

requirements at the sample position (inside the sample holder) are less stringent as only heat dissipated in the sample itself needs to be adsorbed.

Fig. 8 shows the measured cooling power at the sample position in a top loaded sample holder. The temperatures below 50 mK were measured using a nuclear orientation thermometer and above 50 mK using a calibrated ruthenium-oxide temperature sensor [26], both mounted at the sample position. The heat load was supplied by a resistive heater mounted nearby.

The base temperature at the sample position was found to be just over 9 mK and the cooling capacity available at 100 mK in excess of 120 μW. This is reduced slightly from the cooling power available at the mixing chamber plate itself (typically 200–400 μW) due to the finite thermal impedance between the loaded sample holder and the docking station, but as all experimental services are anchored directly to the refrigerator (and not to the sample holder) this reduction poses no problems for experiments.

4. Conclusions

We have shown that cryogen-free dilution refrigerators equipped with sample loading mechanisms are a flexible experimental platform, and are the ideal test bed for quantum device characterisation and development.

The engineering of such a sample loading arrangement for either top or bottom sample loading has been described, and we have shown that the performance attained in terms of the base temperatures at the sample (below 10 mK) and the microwave characteristics of the (up to 14) coaxial lines that are available at the sample position are as good as can be achieved mounting a sample directly on the refrigerator, but that the experimental turn-around time has been reduced from days to a few hours.

4.1. Application examples

The versatility of the sample loading system is demonstrated by the wide range of applications to which they have been applied. Fig. 9 shows some specific examples of experimental data, from different laboratories, obtained using such sample exchange devices.

Fig. 9(a) shows the current generated by a so-called single electron pump used to realise a quantum standard for electrical current, as measured on a top-loading system. In this case the pump is made from graphene patterned into two nanometre size islands separated by tunnel barriers. By applying high frequency signals (with well defined waveforms) to gates in close proximity to the islands, individual electrons can be made to jump from island to island and hence produce a measurable electrical current [37]. For these experiments low temperatures are important to minimise thermal excitations that would produce unwanted tunnelling events and the drive frequency needs to be as high as possible to create a suitably large current. For these reasons well thermalised, high-fidelity microwave lines to the sample are extremely important.

Fig. 9(b) shows the longitudinal and transverse resistivity measured in a δ-doped GaAs–AlGaAs quantum well as a function of magnetic field as measured on a bottom loading system [38]. For these experiments high magnetic-fields and low electron-temperatures in the wiring to the sample holder are required. The quasiparticles of the fractional quantum Hall effect state at Landau-level filling factor $\nu = 5/2$ are predicted to obey non-abelian statistics which could allow for the development of topologically protected qubits [39] for quantum computation.

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